Generation of correlated photons in controlled spatial modes by down-conversion in nonlinear waveguides

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Abstract

We report the observation of correlated photon pairs generated by spontaneous parametric down-conversion in a quasi-phase matched $KTiOPO_4$ nonlinear waveguide. The highest ratio of coincidence to single photon count rates observed in the 830 nm wavelength region exceeds 18%. This makes nonlinear waveguides a promising source of correlated photons for metrology and quantum information processing applications. We also discuss possibilities of controlling the spatial characteristics of the down-converted photons produced in multimode waveguide structures.

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Spontaneous parametric down-conversion is a well-established and practical method for generating pairs of correlated photons. Such pairs are a key ingredient of many experiments testing the foundations of quantum mechanics and in quantum information processing.[1] Correlated photons have been also used in a number of metrologic applications.[2–4]

In this paper we report observation of two-photon correlations in the spontaneous parametric down-conversion generated in a quasi-phase-matched $KTiOPO_4$ (KTP) waveguide using a $\chi^{(2)}$ nonlinearity. As a source of correlated photon pairs, such nonlinear waveguides present several essential advantages over bulk crystals, the typical medium for such sources. First, the technique of quasi-phase-matching (QPM) allows one to utilize larger nonlinear coefficients in some materials, thus leading to substantially higher two-photon production rates. Secondly, the waveguide structure provides a means to control precisely the spatial characteristics of generated photons, as the down-conversion process is confined to well defined transverse modes.[5] Appropriate control of the spatio-temporal mode structure of the photons is a critical issue in experiments involving interference between multiple photon pairs.[1] When bulk crystals are used to realize the parametric process, high visibility of the interference can be achieved only by heavy spatial filtering of the downconversion signal, which dramatically reduces the useful fraction of photon pairs. In contrast, down-conversion in a nonlinear waveguide can provide output in a single spatial mode, which ensures good interference without filtering with a significantly larger sample of photon pairs. This feature, combined with the potential of engineering the temporal properties of the down-converted photons in QPM structures,[6] opens up novel possibilities to control the spatio-temporal characteristics of correlated photon pairs. The use of nonlinear waveguides thus provides a route to the efficient, if random, generation of "heralded" single photons, alternatively to solid-state sources.[7]

Observation of parametric down-conversion in nonlinear waveguides has been the subject of three recent experiments. Two of them[8,9] consisted in detecting Hanbury Brown-Twiss type coincidences on the whole down-conversion signal divided by a 50:50 beam splitter. The third experiment[10] measured a Franson-type two-photon interference effect using an unbalanced Michelson interferometer. A novel feature of our experiment is that we have undertaken the effort to separate *all* the photon pairs of interest into two different spatial paths with the help of a spectrographic setup. Using this technique, we have been able to demonstrate explicitly strong correlations between photons of different frequencies. The central objective of our approach was to show that treating one path as a trigger, one is able to collect effectively all the conjugate photons in the second path. Thus the quantity of primary interest in our experiment is the ratio of coincidences to single trigger counts, and the setup presented below can be viewed as a scheme for generating single photons in the temporal slots defined by the pump pulse, with the arrival time known to a femtosecond precision.

The experimental setup is depicted in Fig. 1. The output of a modelocked Ti:Sapphire oscillator is first doubled in a type-I BBO crystal to generate blue pulses with a central wavelength 418 nm and a bandwidth of 5 nm, polarized perpendicularly to the plane of the figure. The blue light is focused using a 20× microscope objective on the input face of a 1 mm long quasi-phase-matched KTP waveguide. The production and the characteristics of the sample used in our experiment have been described elsewhere.[11,12] The light power injected into the waveguide, measured before the objective, is about 22 μW. The bandwidth of the down-converted light for the parameters of our experiment exceeds well over 100 nm, and the

down-converted photons have the same polarization as the pump field.

The output from the waveguide is coupled out with a laser-diode collimating lens, and transmitted through an RG665 red filter and a half-wave plate rotating the polarization by 90^o. The separation of the twin photons is performed using a zero dispersion line employing two Brewster-angle SF10 prisms and two $f = 10$ cm lenses. In the Fourier plane after the first prism, a multimode fiber tip mounted on a translation stage is used to collect the trigger photons and send them to a fiber-coupled photon counting module. The FWHM wavelength range collected by the fiber tip is about 6 nm. A second element placed in the Fourier plane is a razor blade used to block the low wavelength signal photons which are not conjugated to the trigger photons. This lowers the single count rate on the signal detector, thus reducing the number of accidental coincidences. The remaining signal photons are recombined into a single beam using a second lens and a prism, and focused onto the active area of a free space photon counting module EG&G SPCM-AQ-CD2749. The half-wave plate and all the lenses placed in the down-conversion beam have a broadband antireflection coating in the 800 nm region. The position of the fiber tip is calibrated in terms of the coupled trigger photon wavelengths by sending through the waveguide light from the laser operated in the cw mode at several wavelengths in the range 840–870 nm.

The electronic signals from the photon counting modules are shaped using discriminators to standard NIM logic pulses with a 5 ns width. These pulses are sent to counters measuring the single rates R_s and R_t of the signal and trigger photons, and also feed inputs of an AND gate, providing the coincidences whose rate R_c is measured by a third counter. In Table 1 we present the count rates obtained over a 300 s counting interval for several positions of the fiber tip collecting the trigger photons. The dark count rates, measured with the blocked blue pump beam, were below 100 Hz for the trigger fiber-coupled module, and below 8 kHz for the free-space signal module.

The maximum ratio of coincidence to single counts observed in our experiment is 18.5%. After correcting for accidentals which results in a minor few percent change, this figure can be considered as the overall detection efficiency of the signal photons, including all the losses since their generation in the waveguide. The main source of imperfect detection is probably the non-unit efficiency of the free-space photon counting module used in the setup, which was optimized for 630 nm, including the wavelength-specific antireflection coating of the photodiode. Another important source of losses may originate from the design of the waveguide itself, which includes non-guiding sections having the same optical characteristics as the surrounding bulk crystal.[11]

The highest ratio of coincidences to singles, exceeding 75% at 702 nm after corrections for losses, has been so far reported by Kwiat *et al.*[3] Typical coincidence count rates observed by them were roughly ten to twenty times lower than our data, at similar pump powers. In their experiment good spatial correlations between the down-converted photons were ensured by spatial filtering to a well-defined transverse wave vector, and also by the use of a long nonlinear crystal, which introduced more stringent phase-matching conditions. It should be kept in mind, however, that at the same time this strengthens the frequency correlations between the down-converted photons.[13] Consequently, spectral filtering of the trigger photon path leads to a much narrower bandwidth of the the signal photons. The essential advantage of nonlinear waveguides is that the shorter length allows for an efficient generation of "heralded" photons in broadband, possibly femtosecond, wavepackets, while retaining good spatial control. We note that the generation of single photons in well defined spatio-temporal modes is possible also in thin bulk crystals by appropriate filtering of trigger photons, as demonstrated in a recent experiment by Lvovsky *et al.*,[14] but at the cost of extremely low production rates.

The nonlinear waveguide used in our experiment supports several modes at both the pump and down-conversion wavelengths.[12] However, we will now show the multimode structure of the down-conversion signal can be in principle suppressed by exploiting the modal dispersion in the waveguide. In order to discuss this, let us consider the wave function describing the generated photon pairs.[13] In a waveguide, this wave function is a superposition of the terms of the following form:

$$|\psi_{lmn}\rangle = \int d\omega_s \int d\omega_i \, \alpha(\omega_s + \omega_i)\Phi_{lmn}(\omega_s, \omega_i) \times \hat{a}_m^\dagger(\omega_s)\hat{a}_n^\dagger(\omega_i)|\text{vac}\rangle, \tag{1}$$

where ω_s and ω_i define the signal and the idler frequencies, respectively, $\alpha(\omega)$ is the spectral envelope of the pump pulse, $\Phi_{lmn}(\omega_s, \omega_i)$ is the phase matching function, and $\hat{a}_m^\dagger(\omega_s)$ and $\hat{a}_n^\dagger(\omega_i)$ are the creation operators for the specified frequencies and modes. The indices lmn label the triplet of the pump mode l and the pair of the signal mode m and idler mode n. The relative weights of the components $|\psi_{lmn}\rangle$ in the complete superposition are defined by the coupling strength of the pump field to a specific waveguide mode, and by the overlap of the pump mode with the product of the down-conversion modes.

In Fig. 2 we plot $\Phi_{lmn}(\omega_s, \omega_i)$ for several different triplets of the modes, using the dispersion data from Ref. 12. It is seen that the phase matching functions corresponding to different triplets occupy separate regions

of the plane of the frequencies ω_s and ω_i. According to Eq. (1), down-converted photons are generated only for pairs of frequencies ω_s and ω_i whose sum lies within the bandwidth of the pump pulse. Thus, if we select the pump pulse spectral amplitude $\alpha(\omega_s + \omega_i)$ such that it overlaps only with a single phase matching function $\Phi_{lmn}(\omega_s, \omega_i)$, then the signal and idler photons are effectively generated in single spatial modes.

In conclusion, we have observed correlated photon pairs in controlled spatial modes generated by down-conversion in a nonlinear waveguide. Compared to down-conversion in bulk crystals, this process has several important advantages, including high brightness and control of the spatial characteristics of the produced photons. These features make nonlinear waveguides a promising source of nonclassical radiation in quantum information and metrology applications.

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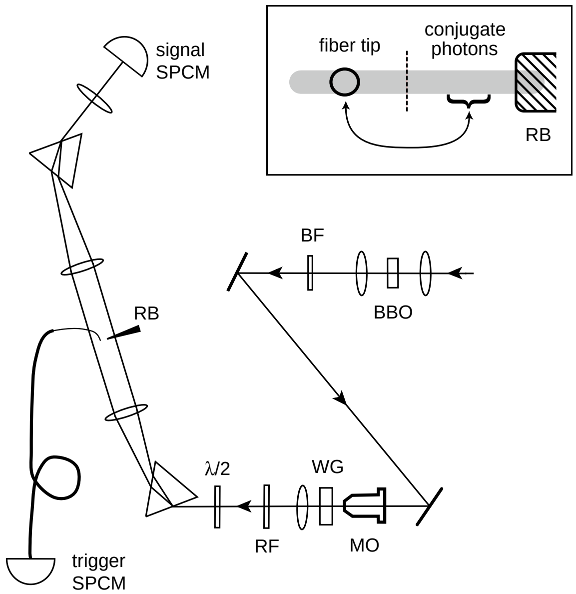

Fig. 1. Experimental setup for detecting correlated pairs of photons. BBO, beta-barium borate crystal for second harmonic generation; BF, blue filter; MO, microscope objective; WG, nonlinear waveguide; RF, red filter; RB, razor blade; SPCM, single photon counting module. The inset depicts the separation of the signal and trigger photons performed in the Fourier plane after the first prism.

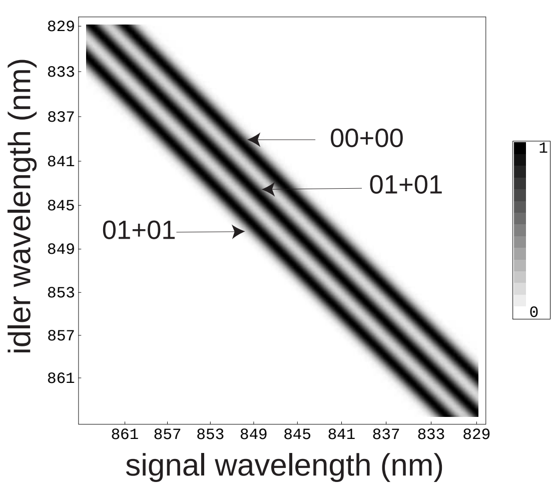

Fig. 2. Phase matching functions for down-conversion from the $l = 00$ pump mode to several pairs of the signal and idler modes. The first-order QPM structure is assumed to have the period 3.9375 μm and the length 1.3 mm. All the parameters of the waveguide are taken from Ref. 12. For convenience, the frequency axes are labeled with the corresponding wavelengths.

Table 1. The signal R_s, trigger R_t, coincidence R_c, and accidental coincidence R_{acc} count rates for several positions of the fiber tip, labeled with the central wavelength λ_c coupled to the fiber. The statistical errors are of the order of or smaller than the lowest digits shown.

λ_c (nm)	R_s (kHz)	R_t (Hz)	R_c (Hz)	R_c/R_t (%)
909	726	3755	671	17.87
897	582	4866	859	17.66
885	702	5692	1055	18.54
872	584	6397	1171	18.31
860	403	7473	1341	17.94
848	277	8149	1409	17.29